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A Thermodynamic Model for the Global Economy and Its Implications for Macroeconomic Theory and Policy Formulation

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Abstract

Over recent decades the share of income produced by global the economy has increased for capital and decreased for labour. Picketty's analysis of wealth and income data implies that there is increasing inequality in income share developing in economies including advanced economies. Further investigation by the International Monetary Fund (IMF), International Labour Organization (ILO) and the Organization for Economic Cooperation and Development (OECD) confirms that capital's share of income is increasing versus labour's share but the data does not fit with Picketty's r > g growth model, instead indicating that technology is involved. This paper presents a physical model concept for an economy and the global economy that explains how and why capital's share of income is increasing at the expense of labour and what policymakers need to do to adjust this trend. The macroeconomic policies that correct this trend have also significant concomitant benefits—they address strategic risks such as global warming which are physically linked by the way the economy currently functions through technology. Current policy is driving and increasing income inequality. Physical evidence based macroeconomic policymaking such as that advocated in this paper, can manage these long term risks.

Keywords

Thermodynamic Model, Global Economy, Macroeconomic Theory, Policy Formulation

1. Introduction: Thermodynamic Factors Active in the Biosphere and Global Economy

Global macroeconomic policy formulation is presently dominated by neo-classical economic theory [1] [2]. For all its earlier successes towards the latter half of the twentieth century, neo-classical economics lacks any explanatory power for the current state of the global economy [3]. This lack of explanatory capacity is now significant, because there are physical factors which only became restrictions once the absolute level and intensity of the global economy within the biosphere attained a particular level. The failure to accommodate physical factors in neoclassical economics also results in the neo-classically based macroeconomic policymaking failing to identify significant correctable inefficiencies that could be managed if neo-classical growth theory could accommodate macroscopic physical influences. An example of "significant" in this context is that increasing inequality between the flow of income between capital and labour. This is significant because failure to address in appropriate policymaking is increasing income inequality in advanced as well as developing economies and hence the undermining the political stability and sustainability of current policymaking.

The aim of this paper is to provide a conceptual model of global macroeconomic growth that accommodates the fundamental macroscopic physical factors affecting growth. In doing so it is necessary to re-write neo-classical economic growth theory in a form that accommodates the fundamental macroscopic physical factors affecting growth. This paper provides a review of recent global macroeconomic history to derive explanations for observed macroeconomic trends. The latter analyses will be based on the development of a proposed growth model to be used as a tool to investigate physical and macroeconomic relationships. Assessments will also make allowance for recent advances in economic knowledge such as behavioral economics. These analyses and assessments are being undertaken to derive recommendations for new potential macroeconomic solutions for policymakers to investigate, which will be stated in this paper.

Alternative economic models that take physical factors and in particular, thermodynamic factors into account have already been proposed by the pioneers of environmental economics, including Georgescu-Roegen, Daly, Constanza, Pearce and Ayres [4]. This paper builds on their legacy and on Ayres's work in particular. Environmental economics has begun to exploit the ability of physics to provide a macroscopic theory and basis for systems analysis in the form of the laws of thermodynamics.

The second law of thermodynamics also provides a description of how thermodynamic information and the fraction of energy that carries out work (termed exergy) are related. Recently, this relationship has shown to play a key role in biological system development and the relationship between life and the environment—of which human economic activity is a part [5]. This paper takes that original concept and integrates it into a physically referenced macroeconomic model of the global economy. The new model explores the physical constraints on technology and the downstream economic risks that can arise from technology with regard to economic growth.

Other recent analysis of macroeconomic trends that needs to be taken into account in this paper is Picketty's analysis of the relationship between income returns between capital and labour and how that has recently begun to shift towards capita after remaining previously constant historically. Regardless of the economic approach there are only three primary *physical* factors of production:

- *exergy* (that fraction of energy available in an energy source for the performance of work) and hence, energy
- *information* (of which knowledge/human capital and market operation is a function)
- *materials* (the material resources for production)

The laws of thermodynamics have profound economic consequences. While energy is conserved, exergy is not and exergy is consumed during work. Entropy is a measure of the quality of a resource. A high entropy fuel is a low exergy (inefficient) fuel. A high entropy material resource such as a metal ore for example, has a low metal concentration and requires more work to process. Material resource quality thus relates to cost of production. These factors and how they relate to conventional macroeconomic assumptions will now be investigated.

2. Conceptual Model Derivation: The Physical Global Economic Model (PGEM)

The thermodynamic properties representing human economic activity are described in **Figure 1**. **Figure 1** is a systems diagram for the general materials and energy balance for a production process in an economy and situates that economy in its "local universe"—its environment. For the global economy this is the biogeosphere. Production generates wastes which in turn dissipate materials into the environment-materials are discharged mixed into the atmosphere and aquatic environment, which in effect dilutes them. When processed material wastes are discharged to the air, water or land, those materials may adversely affect the environment and may also affect human health (downstream cost risks conventionally dealt with as externalities). The system elements of **Figure 1** need to be expanded to describe economically functioning basic elements of the global economy. The principal economic inputs that need to be added to the model are labour, capital, energy and materials. Outputs need to include products (GDP as example metric), processing residuals (meaning waste products) and the surplus capital that maintains economic activity. This model has neo-classical elements: capital in the model refers to fixed, working and financial capital. A relevant global model has to be based on a medium of exchange (money) supported market system, just as the global market is. In terms of information, the market represented is assumed to use price as its principal information.

The system is the global macro-economy and the boundary drawn is that of the global market. The "local universe" in thermodynamic terms is set at the environment of the Earth (the biogeosphere) for physical material elements. The global macroeconomic physical model presented in **Figure 2** has 4 principal inputs: materials, energy, labour and capital. Capital inputs include money and capital

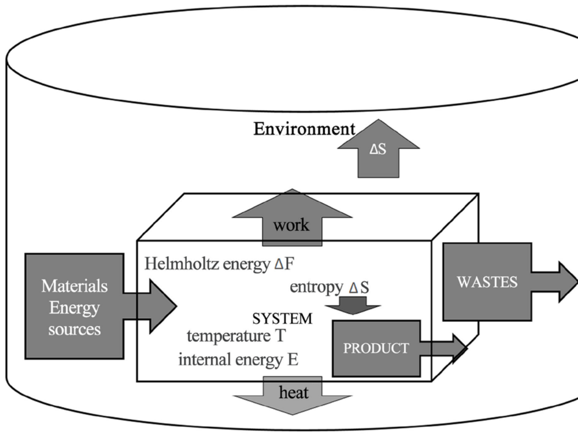

Figure 1. A systems diagram for human labour, or a mechanized manufacturing process. The person or process takes in materials (food, fuel, materials) as feedstock for processing; the person or process is able to do physical work from utilization of those feedstock materials but also discharges waste materials including pollutants into the system surroundings (environment). As production (of goods or service provision) does so, the *entropy* of the ultimate environment (universe) always increases as the use of materials by the system (person or process) *decreases entropy within the system* in the process of *producing free energy* (to support physical work) and/or *increasing order within the system* (to build a person or product).

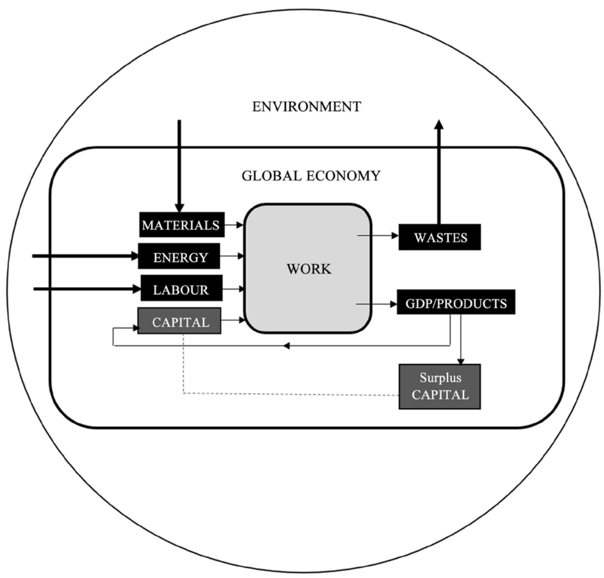

Figure 2. A systems diagram for a conceptual physical model of the global economy. In physical terms, this Physical Global Economy Model (PGEM) is a thermodynamically open, non-equilibrium, dissipative system. From the restrictions imposed by the second law of thermodynamics it has to disseminate material into the environment. It is dependent on physical work provided by labour and machines (capital) to produce anything, which is in turn dependent on a free energy *i.e. exergy* input to carry work out. Production hence requires both energy source inputs for labour and capital (machines) and material resources, extracted from the environment. Note that material resources (energy and materials) are not treated as intermediates. The PGEM concept-model has the following elements: Production (GDP), capital (K), Labour (L), Energy (E), Materials (M) and Wastes (W).

goods, hence a feedback exists between products and capital inputs for a production cycle. Outputs include wastes and products (which can be monetarized as GDP or similar measures (e.g. Gross Value Added) and surplus capital, of which some or all can be recycled to fund a subsequent production cycle (see **Figure 2**).

In *material* terms, this model is assumed closed at the planetary boundary (upper atmosphere), ignoring losses from the atmosphere to space (atmospheric escape). This physical characteristic has an economic implication for the global model: the global economy is *closed*. Imports and exports; trade, is irrelevant to the global model but is necessary when addressing the performance of individual economies. In *energy* terms, the model is *not* closed at planetary boundary due to solar radiation and its critical energy input to Earth.

The PGEM is conventional in its general macroeconomic outlook, *i.e.* there are two principal activities assumed in the economies it describes, production and consumption with producers and consumers, these activities relating to supply and demand respectively. The conventional basic relationship for demand is assumed:

$$\text{Demand} = Z = C + I + G \tag{1}$$

where C =consumption (\$), I = investment (\$) and G = government spending (\$) and further, the assumption is that consumption is a linear function of disposable income;

$$C = c_0 + c_1\left(Y_D\right) \tag{2}$$

where C =consumption (\$), c_0 = intercept of linear consumption (as a function of disposable income), c_1= slope of linear consumption and Y_D = disposable income (\$).

The PGEM assumes that there is an equilibrium between demand "Z" and production "Y" ($Y = Z$). Within the conceptual global model there are assumed to be are component economies (e.g. 197 component economies in 2017) each with a demand for goods and services described by:

$$Z = C + I + G + X - IM \tag{3}$$

where X = exports (\$) and IM = imports (\$).

The PGEM conceptual model assumes conventional aggregate supply and demand relationships. Neo-classically, growth is described by the Solow-Swan model:

$$Y(t) = K(t)^{\alpha}\left(A(t)L(t)\right)^{1-\alpha} \tag{4}$$

where $Y(t)$ = Total Production (GDP) for year t; $K(t)$ = capital for year t, $L(t)$ = labour capacity for year t, $A(t)$ = technology productivity factor for year t and α = elasticity of output with respect to capital [6] [7].

This relationship is partially based on its precursor, the Harrod-Domar model, which did provide some explanatory basis for economic cycles (boom and bust) but assumed fixed relative price for capital and labour. This also means that the value for elasticity of capital and labour was typically set fixed at the unitary level *i.e.* a value of 1, to allow a constant ratio of labour and capital. Although this fixed relationship has held true for a long period of time [8], that relationship has changed lately [9] and appears related to growth in income inequality. This change makes the Harrod-Domar model unsuitable for this analysis. However, the Solow-Swan growth model itself has deficiencies, especially with regard to the physical basis for production.

The PGEM also assumes Cobb-Douglas production functions apply:

$$Y = AL^{\beta}K^{\alpha} \tag{5}$$

where Y = annual Total Production (real GDP); K = annual capital input, L = annual labour capacity (hours) year t, A = Total Factor Productivity (TFP), α = output elasticity of capital and β = output elasticity of labour.

Robert Solow's model has also been modified to include other factors, such as human capital by Mankiv, Romer and Weil:

$$Y(t) = K(t)^{\alpha} H(t)^{\beta} \left(A(t)L(t)\right)^{1-\alpha-\beta} \tag{6}$$

where $Y(t)$ = Total Production (GDP) for year t; $K(t)$ = capital for year t, $H(t)$ = human capital for year (t), $L(t)$ = labour capacity for year t, $A(t)$ = technology productivity factor for year t and α = elasticity of output with respect to capital and β = elasticity of output with respect to human capital.

The problem with these conventional analysis tools is they have no direct physical relationship to the real world. One aspect of this deficiency is that the productivity factor functions as an undefined adjustment factor, to fill the gap that emerges when empirical data is analyzed. The Mankiv, Romer and Weil revision of the Solow Swan model is an attempt to close this gap but the definition of human capital still gives no formal physical definition of what constitutes technology.

2.1. The Technology Question: What Is Technology?

Technology is in effect tool use and its function is to increase human physical work capacity. In thermodynamic terms, physical work requires energy and the fraction of energy that is consumed in physical work is exergy. Physical work also includes utilization of information including data processing and analysis. The physical work that a laborer can carry out is increased by mechanization and in the current global economy which includes administrative and other tasks which can be routinized and then mechanized [10]. Mechanization is the core of industrialized economy technology. This is the basis of capital assets increasing the productive output of labour and the basis for capital assets replacing labour. Mechanization goes *beyond* agriculture and industrialization and includes mechanization of services.

There are downstream consequences from mechanization. One is that the technology replaces labour with machines and an associated energy demand to operate those machines. In thermodynamic terms, the physical resource used is exergy and it is through the analysis of exergy that Robert Ayres and his co-workers have demonstrated that the technology productivity factor of the Solow growth model is fully described in the long term by analysis of exergy in an economy [3] [11] [12] [13]. The exergy demand of an economy represents the physical work carried out by labour and machines—labour and the capital assets. Another downstream consequence of mechanization is that machine technology introduces new informational requirements for operators; the information threshold for a production operation is raised to that required to successfully operate the system of machines. This in turn requires investment in the information utilization efficiency of labour-education or training, either by the producer (I) or by Government (G) (see Equations (7) and (9)).

The Mankiv, Romer and Weil revision of the Solow Swan model is an attempt to better describe this factor, in their case, human capital, which exerts its own demands in terms of improving the informational capability of labour. The services and goods required to accomplish this will be described in this paper as *soft infrastructure* to distinguish them from the physical "hard infrastructure" which also plays a role in the service provision by soft infrastructure.

The Solow growth equation may be revised to account for the physical factors in PGEM:

$$dY/Y = \alpha\left(dK/K\right) + \beta\left(dL/L\right) + \gamma\left(dE/E\right) + \delta\left(dM/M\right) + \varepsilon\left(dW/W\right) + \zeta\left(dt/t - t_0\right) \quad (7)$$

where $\zeta \equiv (t - t_0/Y)\ (dY/dt)$ and where dY = annual total production (real GDP); dL = annual labour capacity (hours/year), dE = annual energy demand kWh, dM = annual material mass used (kg), dW = annual material mass discharge to environment (kg), α = outpu telasticity of capital, β = output elasticity of labour, γ = output elasticity of capital, δ = output elasticity of materials, ε = output elasticity of waste discharged. No materials balance assumed, *i.e.* waste discharge is not assumed = 1-material used.

2.2. Externalities

The PGEM concept shows that waste production is an unavoidable process and the global market will always disseminate waste into the environment. Where this causes harm to the environment it degrades the potential value of the environment and creates potential for harm to the human population/labour force and degradation of natural capital. This economic harm can be mitigated through deployment of capital, physical work and use of material resources to actively mitigate waste discharge harm. These costs of production are typically not fully accounted for *i.e.* not adequately valued or monetarized and typically "socialized" in terms of where the costs are levied in the market. The global water industry and its provision of water cleaning and sanitation is an example of an essential service underpinning production. Externalities are an area of deficiency in conventional macroeconomic analyses from a physical viewpoint. The revised Cobb-Douglas production function in Equation (7) implies that material resources, energy consumption and waste production are direct costs production.

Industrialized global economic growth creates a significant energy and hence fuel demand. This fuel demand is currently dominated by fossil fuels and that in turn creates environmental damage to the atmosphere through emissions [14], part of the overall economic damage wrought by greenhouse gas emissions [15]. The principal greenhouse gas is carbon dioxide and the Kaya identity describes how its production is related to economic activity:

$$\text{CO}_2\,\text{Emissions} = P\left(\frac{(GDP}{P}\right)\left(\frac{E}{GDP}\right)\left(\frac{CO_2}{E}\right) \quad (8)$$

where P = Population, E = Energy (kWh) × $GDP = GDP$ ($), CO_2 = kg CO_2 [16]

The environmental and natural capital impact of industrialized global economic activity includes solid and liquid emissions as well as gases [11] [17] [18]. These activities also lead to significant environmental damage and habitat loss. The Earth's stock of natural capital is the source of the Earth's range of ecosystem services.

2.3. Consideration of Markets, Timescales and Wealth

The market in which goods and services are purchased works on one form of information—price (the information relating perceived value of a good or service to the medium of exchange used in the market). One aim of this paper is to capture the state of the art in physical terms for the global economy and global market functionality. Recent critical advances in economics are not confined to establishing physical factor functionality; psychology has provided a basis for behavioural economics. Price determination is described by utility theory in neoclassical economics, where price is assumed to be determined objectively by rational agents. However, behavioral psychology has now established that utility theory was incorrect. Human value determination is subjective, not objective [19]. A physically referenced model such as PGEM, should also accommodate the economic behaviors demonstrated by behavioral psychology and now part of behavioral economics (*i.e.* [20] [21] [22]) to take account of critical behavioral traits in economic decision-making such as loss aversion and confirmation bias.

A conceptual re-analysis of global macroeconomics and capital also needs to consider the relationship between wealth and production. Wealth is composed of more than just capital assets, with land being a significant proportion of *per capita* wealth [23]. Land is also subject to thermodynamic (entropy) effects on its value, from general environmental degradation, sea level rise and specifically, from entropy in production of which the most obvious measure is soil quality erosion. Trends in global macroeconomic development will now be analyzed based on the PGEM concept and the relationships implied in Equation (7).

3. Economic Objectives and Typical Global Economic Development

Macroeconomic activity is also a function of government policy formation. In physical terms, there are development factors that governments seek to improve for the common good of their citizens. Many of these factors are captured in other terms than GDP. The Human Development Index (HDI) is an example, with advanced economies tending to have the highest HDI scores. Government policies in most democracies typically seek to improve HDI factors by intent even if not achieved in implementation (**Figure 3** and **Figure 4**).

The most advanced economies typically have the highest HDI ratings *and* high *per capita* GDP. This is no coincidence: advanced economies are mechanized and have a range of physical assets; hard infrastructure and soft infrastructure to support high productivity. Global growth over most of the last two decades has been provided mainly by BRIC countries. These are an example of the typical development path which leads towards an advanced economy, in which mechanization of all sectors increases the output from labour by increasing the productivity of labour. They (BRIC) also lack the full range of "hard" and "soft" infrastructure supporting a G7 level of GDP productivity *per capita*. That infrastructure itself exerts a significant depreciation burden (Capital Maintenance cost) on G7 economies that BRIC countries do not yet bear to the same degree. Consequently, the globalized economy is in effect a difference engine: lower labour costs and capital maintenance costs in developing economies provide a basis for rapid productivity growth through mechanization where internal and external capital can be secured. The growth shown via mechanization in India and China alone to date, has been responsible for the bulk of recent global growth. The G7 only represent 9% of the global population today whereas the

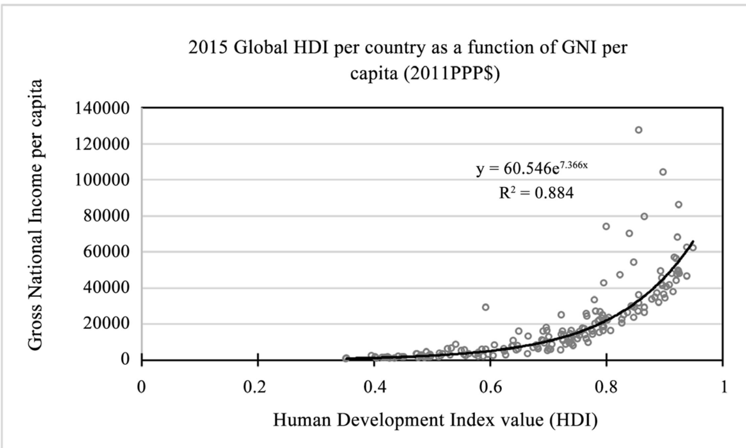

Figure 3. Plot of Human Development Index (HDI) against GDP per capita (real; purchasing power parity $) for individual countries. HDI is strongly correlated to GDP per capita so economic growth and productivity increases provide a route towards the current highest development levels. There is a feedback element here to this development path because some HDI elements that contribute to increased wellbeing for labour also increase productivity. The reason GDP is strongly correlated to HDI is that advanced economies go through a development path where key physical economic infrastructure and institutions, including what may be termed "soft infrastructure" are constructed , then maintained to sustain and optimize economic growth. The range of Government directed or Government provided assets towards this goal, for which taxation is levied, also includes physical hard infrastructure provision and maintenance. Data from World Bank-World Development Indicators *wdi.worldbank.org*.

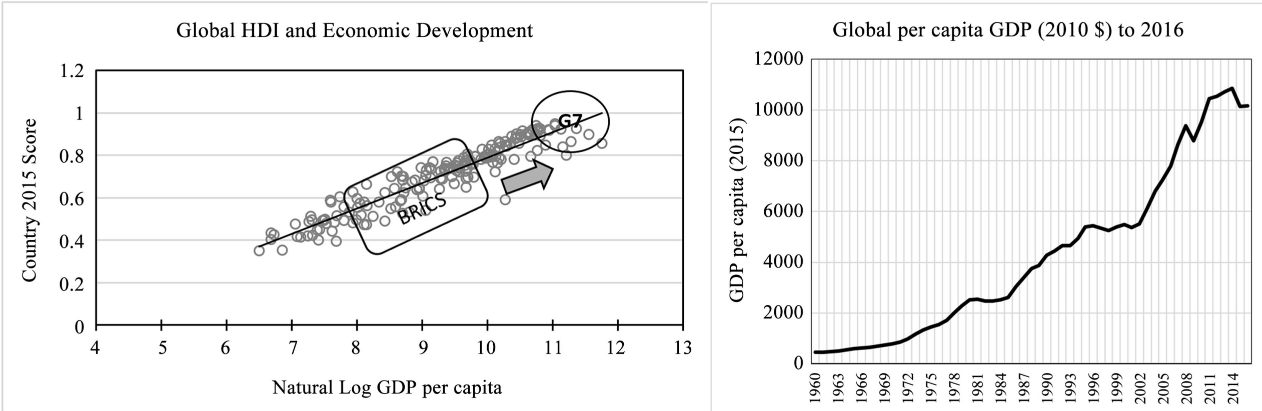

Figure 4. The global economy and economic development path for a developing country. The leading human development blueprint is here illustrated by the G7 states and the economic development path required to arrive at a G7 economy is illustrated by the key developing countries identified by McNeil (BRIC countries). The BRIC have significantly lower GDP *per capita* than the G7 but also have lower per capita income and lower *per capita* costs. The leveraging of greater physical work productivity from labour has created physical structural differences between advanced and emerging or developing economies which appear as a range of supporting physical hard infrastructure including that facilitating the soft infrastructure necessary to maximize returns from labour (e.g. education; health services etc.). These development factors are captured in conventional macroeconomic tools such as the Swan-Solow models and Cobb-Douglas production factors in their capital (K) and Labour (L) production factors. The productivity offered by mechanization goes beyond high exergy mechanical tasks and includes the mechanization of informational tasks especially in an advanced economy. The productivity of advanced economies depends on mechanization and mechanization is the technology "engine" of the Swan-Solow technology productivity factor and the Cobb-Douglas TFP (Total Factor Productivity). The present level of global GDP relies on mechanization. Data from World Bank-World Development Indicators *wdi.worldbank.org*

BRIC countries provide 42% of the global population. Consequently, the majority of the planetary economy is now industrializing and mechanizing.

4. The Physical Anatomy of an Advanced Global Economy

Advanced economies develop assets to maximize both the physical work capacity and value of labour, through the deployment of the necessary capital assets and supporting hard and soft infrastructure. Figure 5 illustrates this development path for the U.K. as a case study. In the U.K., mechanization and its concomitant increase in agricultural returns from labour released labour which was available for mechanized manufacturing while increased agricultural productivity increased agricultural surpluses which in turn which supported population growth. Manufacturing became geographically focused in urban development, with this intensity of development causing environmental impacts that affected key natural resources such as water and waterways and caused severe public health problems which in turn constrained growth. Manufacturing and increased machine technology deployment increased specialization, which increased productivity and but increased demand for a more educated workforce, promoting development of systematic education. Consequently, legislation and regulation then developed to protect public health and the environment to assure sufficient labourproductivity. Population growth then accelerated, minimally constrained by disease.

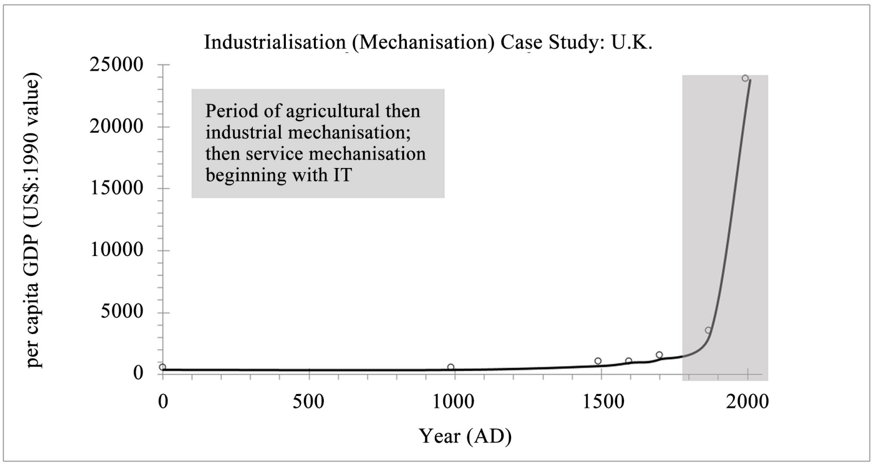

Figure 5. Development path of a modern industrialized economy. For the U.K. which was the first country to fully industrialize, mechanization in agriculture raised productivity in agriculture by increasing per capita productive work. The productivity increases arising from increasing mechanization supported population increases from increased food production. Mechanization and technology development created more specialization which in turn created a demand for increased knowledge, a long term continuous feedback still active now. Part of the return on investment in knowledge development also supported health developments which in conjunction with high agricultural efficiency allowed rapid population growth. Data from Maddison, G. (2013) in the Maddison-Project http://www.ggdc.net/maddison/maddison-project/home.htm, 2013 version.

The underlying pattern of long term development that is occurring here is feedback between the physical work and productive capacity of labour into increasing needs for training and education caused by the deployment of technology in the economy. The physical consequences of the growing dependence of advanced economies on mechanization are a demand for a global minimum level of industrial capacity and a dependence on energy as a substitute with mechanization for human labour.

The Technology Factor: Thermodynamics, Technology Constraints and Technology Needs

Technology is the use of tools to extend human exergy reach and opportunity. In physical terms, technology development in the human economy recapitulates the principal thermodynamic forces acting on organisms for natural selection: the exergy capacity and exergy efficiency of an organism and its information capacity and information utilization efficiency [5]. The same factors drive the development of technology.

Increased technology deployment to maximize the physical work per labourer normally introduces some level of requirement for increased information utilization *i.e.* education and training. In advanced and industrialized economies, the role of technology is best described as mechanization, which describes both the application of technology for increased labourer productivity in physical goods *and* information services. While the former has increased physical productivity for labour and reduced the demand for low skilled labour, the latter is now based on routinization of middle skill level tasks. The most recent changes in labour requirements are being driven by task codification and machine completion of a range of activities in the economy which have previously been delivered by middle-skilled workers.

Technological progress increases both the range and reach of labour. The substitution of labour for capital is a function of technology increasing exergy (work) capacity of a unit of labour. However, the exergy reach (work opportunity) of a unit of labour can also be increased by technology if facilitated by an increase in information utilization efficiency (education or training). The two outcomes may be combining to some degree in one technology or may be mutually exclusive in another. There is therefore no basis to assume technology is neutral is terms of capital and labour share. Technologies are procured by individual producers *to service the producer's own requirements*. In agriculture, mechanization predominantly (but not exclusively) is currently based on increasing the work capacity of labour and displaces low skill labour. This factor is probably responsible for the pattern in change of share of capital and labour in China being different to that seen in more advanced economies [24]. The global economy and the leading (most productive) economies are critically dependent on energy due to their level of mechanization. Fuel production is essential to energy generation and other essential activities such as transport. Energy generation in a transferable form is essential to a mechanized economy. Heat engines are an example of exergy sources for work and production and other key economic functions such as transport. Heat engines include steam engines/turbine systems and internal combustion engines.

Electrification is currently the most effective means of energy transfer across an advanced economy but its generation is fuel inefficient. The lowest efficiency technology in series for fuel conversion to end use is the one that determines its ultimate efficiency. Regardless of fuel energy density, the conversion stage in electrification determines the efficiency of electricity generation before grid transfer losses further erode total efficiency. Steam turbines have a maximum theoretical efficiency of 46% and in practice it is 32% to 42%: both are used with nuclear and coal fuels to generate base load. Typical natural gas fueled electricity generation is even less efficient than high temperature steam at 32% to 38%. These inefficiencies are characteristic of heat engines (which also include the petrol and diesel engines servicing most of the global transport needs). All heat engines are subject to Carnot's observations for second law of thermodynamics limitations on heat engine efficiency:

$$\text{Heatengine efficiency} = \eta = 1 - T_c / T_H \; \eta = 1 - T_c / T_H \tag{9}$$

which is Carnot's theorem, where T_C = temperature of heat sink and T_H = temperature of heat source (degrees K).

The efficiency of the heat engines currently supporting and doing much of the physical work in the global economy is dependent on the difference on operating temperature relative to ambient temperature.

Consequently, only moving to much higher operating temperatures for these systems could increase energy efficiency but as operating temperatures are already dangerous compared to human norms, this has safety considerations. However the most significant consideration is that high energy engines imply very robust materials. New materials development may therefore open a route to more efficient engines—but this has an attached cost in terms of the energy demand for formation of materials capable of high temperature application. New materials development often requires more energy input.

Many modern products or their components are small scale and require work at very small scale. The downside of this physical restriction is lower production rates. The consequences for miniaturized technology are illustrated in the right hand side graph of **Figure 6**. Low production throughput creates a very high specific energy consumption per unit manufactured. Artificially manufactured materials produced to optimize particular material properties usually have an inherently high value, which allows their production to accommodate a very high specific power cost. One example is provided by carbon nano-tubules, where the extremely high unitary high power demand amounts to only 0.2% of the price the manufactured good(s) [25]. Highly effective materials usually have high total cost and a high energy demand.

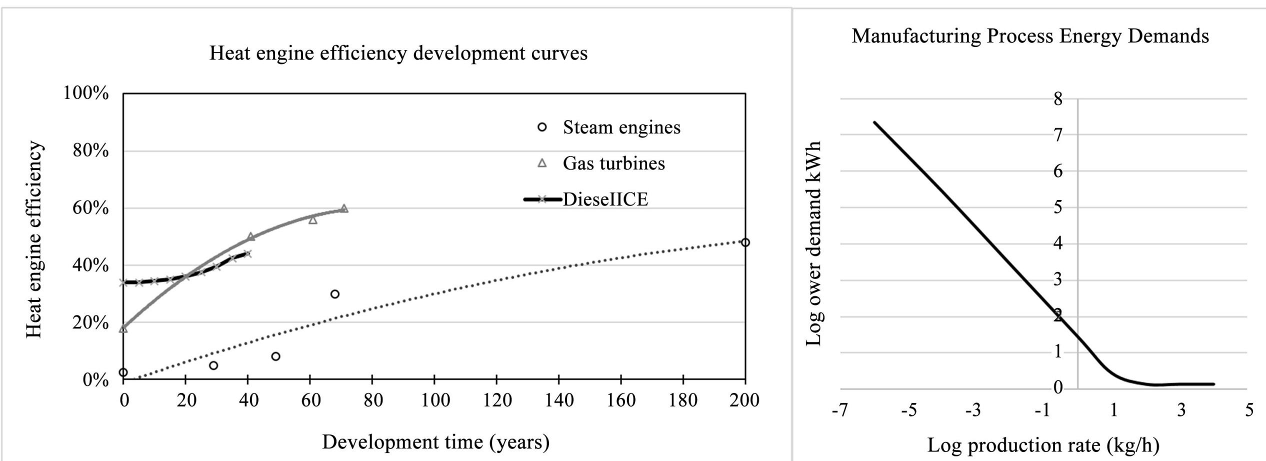

Figure 6. Technology development cycles with the dotted line illustrating the generic sigmoid curve often seen in technology development (left hand side graph). Most technology development, including that of the generic technologies which now dominate the capital asset base of the global economy (such as heat engines for example) follow an "S" shaped development curve in terms of their output efficiency. This begins at concept and bench scale during which technology information (knowledge) is relatively low, on to prototype development and diversification during which the most efficient variants are selected for deployment. This "evolutionary" stage of full scale development provides the fastest rate of development in terms of machine efficiency against physical (thermodynamic and other) constraints. When a technology is mature the understanding of its capabilities; its accumulated information has also been optimized against such constraints and is also mature. A mature technology is typically only capable of marginal improvement as it is operating close to the point of what is physically possible. The right hand side graph, after Gutowski and Sekulic (2010) shows the effects of minaturization: small units often have a lower mass production rate which increases the unit energy requirement. Data from references [17] [25] and Thermal Engineering in Power Systems (Volume 22) of Developments in Heat Transfer Series, International series on developments in heat transfer, v. 22, WIT Press, 2008.

Technology does not operate in isolation. The investment producers make in capital assets and new technology is augmented by a general need for continual up skilling of labour while low demand for low skill labour fluctuates in relation to the intensity and reach of mechanization within an economy. Production capital and technology *per se* exists within a web of upstream (energy provision, materials extraction, logistics, training, etc.) and downstream (logistics, waste treatment, health services, etc.) work and material requirements [26] [27]. The generic physical and economic characteristics of advanced economy technology are those of mechanization, but technology depends on more than machines. Technology development is dependent on information utilization efficiency, which in human terms is a function of knowledge. The development of technology also feeds back into information capacity and capability in an economy, which is more important in economies with a higher services share of wealth creation. *Globally however, there is still a "primary production" from agriculture combined with industrial production that supports and partially creates the global market forservices* (**Figure 7**).

5. A Physical Systems Analysis of Recent Global Macroeconomic History 1980-2016

Advanced economies are typically highly mechanized and have significant structural differences to emerging and developing economies. These physical assets support the level of goods and services productivity which advanced economies can provide but those capital assets and labour capacities also require raw materials to support their needs. The dependence on machine technology creates dependence on energy [3] [11] [12] [13] [28].

The advantage to analyzing the global economy holistically and using those findings for a top down analysis of macroeconomic trends, is that the global economy is materially closed. This means that trade can be dispensed with for the *global* model, until analysis proceeds down to the level of the global component economies (*i.e.* the national economies)—when trade needs to be accounted for. Causation in macroeconomics often reduces to a discussion of whether demand or supply issue is the principal cause of a given events or series of events. Introducing physical factors into these investigations provides a better basis for discrimination between demand and supply and identifying causation between supply and demand.

The PGEM gives us 5 factors of production and hence 5 elasticities for production for capital, labour, energy, materials and wastes. If we consider the technology factors discussed in section 4.1, the period 1980-2016 is one in which the global economy is beginning to mechanize to a significant degree which implies a changes in both degree and depth of mechanization in a growing number of global economies and concomitant increases in information utilization efficiency, including increased knowledge transfer in labour pools. For the Solow model, this will affect the elasticity of labor versus capital in industrializing and mechanizing economies. For PGEM (as defined in Equation (7)), we see 5 elasticities of production which are subject to probable change over this period due to a fundamental physical (second law of thermodynamics) factor-resource entropy. PGEM makes the change obscured in the single technology factor of the Solow model more obvious and gives a basis for policy risk assessment. This level of increasing mechanization and its downstream effects on elasticity of production implies there is no *long term* general equilibrium in this period (1980-2016) because of the physical pressures the global market is exerting on these factors of production (Figure 8 and Figure 9).

Correlation does not imply causation. However, high correlations would be expected between energy and the critical raw materials of production for mechanization (metals and fuels), if mechanization is the principal driver for the Solow technology factor and TFP. Table 1 (IMF Data) shows that this is what we see for the period from 1992 to 2017 when global mechanization grew most strongly.

Of all the common commodities traded, oil and its price is a highly sensitive measure of globalized economic activity once corrected for supply management, due to the dependence of the globalized world economy on inter-country trade and the ubiquity of the internal combustion engine (Figures 10-12).

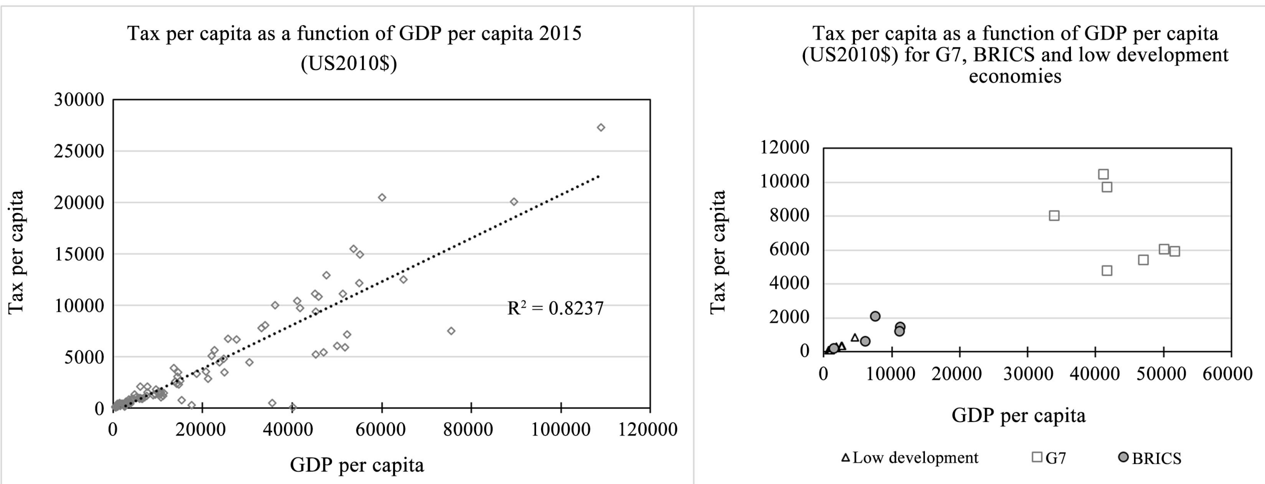

Figure 7. Government contribution to production is significant in a typical advanced economy even though private investment is the critical part of productive capital and can flow in from outside a countries boundaries, especially in a globalized economy. Production does not occur in isolation and is supported by a complex web of soft and hard infrastructure both upstream and downstream of production *per se*. The left hand side graph shows how tax per capita correlates with GDP per capita within the global economy for 2015. When the data is segregated into 3 groups of 7 or 8 countries based on the state of development of their economies (low, developing represents by BRICs and advanced represented by G7), the same pattern of tax per capita increasing with increased economic development (GDP per capita) is replicated (right hand side graph) but with a divergence highlighted between higher tax and lower tax economies. In addition, although direct investment in production in most free economies occurs via private investment, technology development may require a longer term view and greater investment and risk than the market typically wishes to bear (e.g. nuclear energy). Silicon Valley is an example of successful *strategic* government investment in technology development. The global information technology industry was seeded by federal grants in the first instance over 40 years ago, which created a platform for U.S. dominance in information technology that persists today. Data from World Bank-World Development Indicators and *data.worldbank.org/indicator/GC.TAX*.

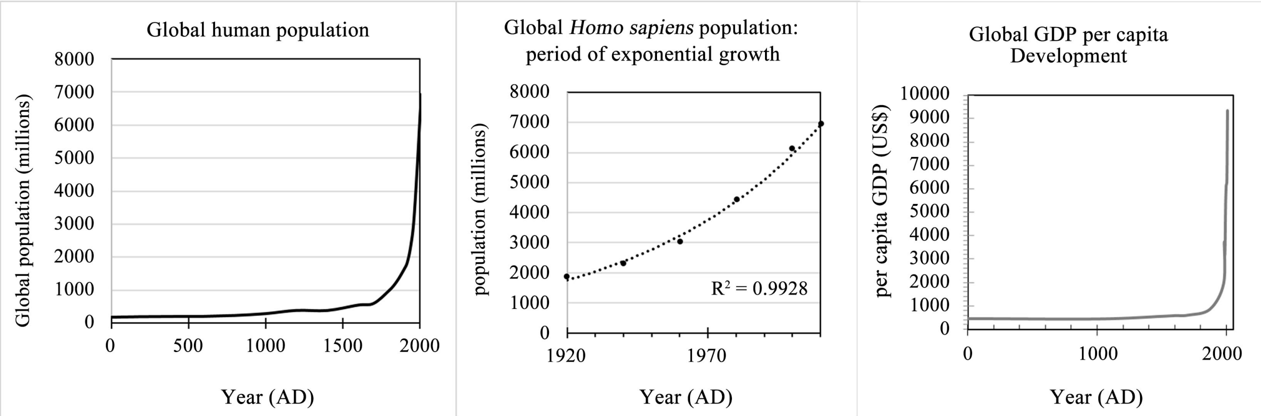

Figure 8. The factors underlying global physical demand trends. Global human population growth has followed and been facilitated by the knowledge growth required to increase economic productivity, part of which physically translates into the development of technology. Industrialization is part of the development path for an advanced economy and introduces universal mechanization. Even when advanced economies choose to off-shore mechanical production and its associated environmental impacts, those economies and the global economy *in toto* still depend on a minimum level of industrial production for the technology supporting the present level of GDP. One consequence of this activity is that it has removed previous natural constraints on human population growth, resulting in the global human population growing exponentially from 1920 to 2000. This has coincided in the last 3 decades with exponential growth in *per capita* demand, resulting in a *super-exponential* demand for the materials and energy required for mechanized economies. Population data from https://ourworldindata.org/world-population-growth and GDP data from World Development Indicators *wdi.worldbank.org*.

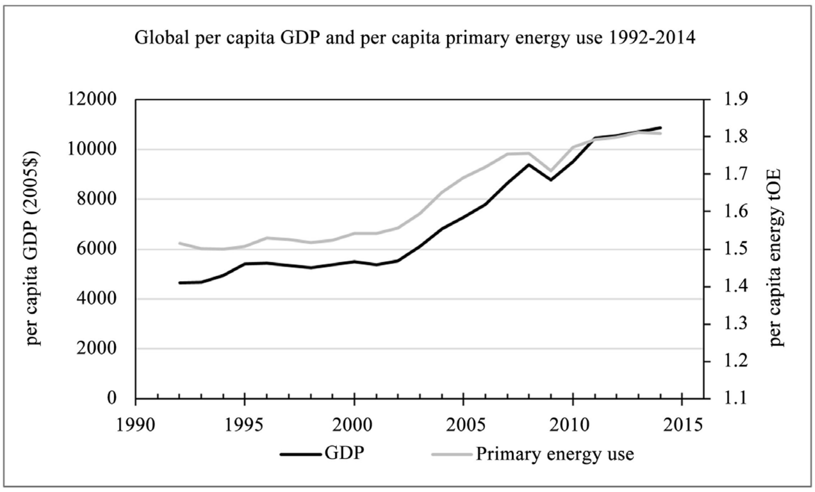

Figure 9. The factors underlying global physical demand trends. Global human population growth has followed and been facilitated by the knowledge growth required to increase economic productivity, part of which physically translates into the development of technology (Global GDP; left hand side graph). Industrialization is part of the development path for an advanced economy and introduces universal mechanization. Even when advanced economies choose to off-shore mechanical production and its associated environmental impacts, those economies and the global economy still depend on a minimum level of industrial production for the technology supporting the present level of GDP. The global economy and its natural capital are still impacted by off-shored economic activity. The global consequence from 1990 to date is convergence between per capita energy demand and per capita GDP, despite increases in energy efficiency in the same period. Data from BP Statistical Review of World Energy 2017 (Underpinning data MS Excel file) and World Development Indicators *wdi.worldbank.org*.

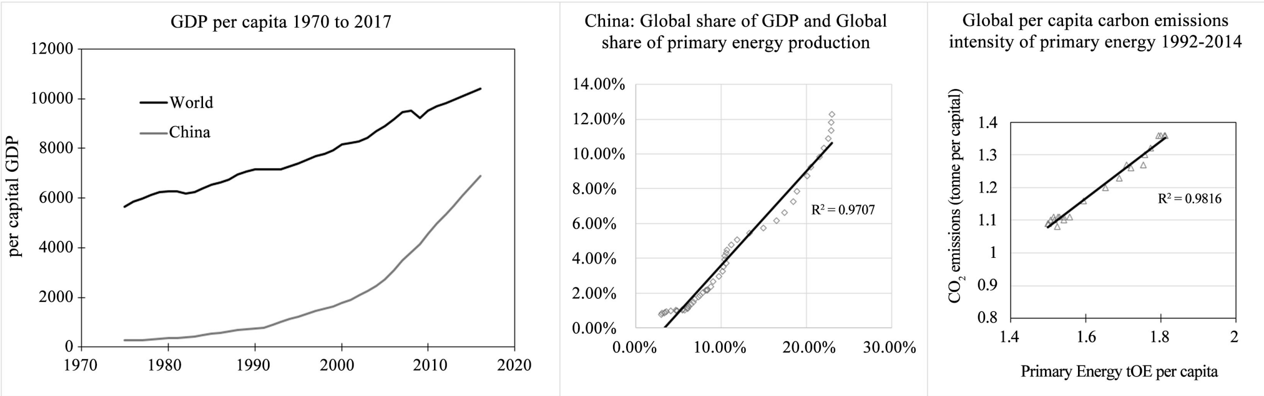

Figure 10. Significantly developing large economies such as the BRIC members China and India have enormous labour capacity and are taking advantage of advanced economy off-shoring while also seeding their own higher value service sector capacity. This level of increased mechanization is increasing the productivity of these economies, with China and India being significant examples because they account for 38% of the global population, so rapid mechanization in China and India, combined with G20 countries, is a picture of a mechanizing *world*. GHG emission data from Boden, T.A., G. Marland, and R.J. Andres. 2017. Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2017. Other data from World Development Indicators *wdi.worldbank.org* and BP Statistical Review of World Energy 2017 (Underpinning data MS Excel file).

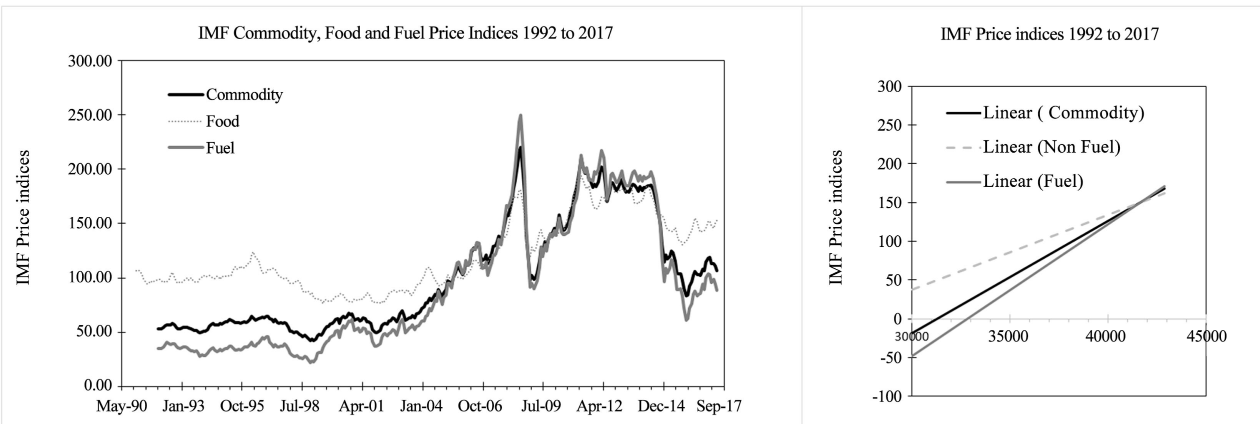

Figure 11. Global commodities prices vary with supply and demand. However, mechanization is heavily dependent on metals as raw materials (among others) for capital asset production and energy for that production and for production asset operations/production in turn. The increase in global mechanization has resulted in real fuel prices and commodity process converging (left hand side graph). The underlying trend of concern is that in the last three decades, within which mechanization has been significantly increasing its role in production globally, commodity and fuel prices have been on a long term upward trends (right hand side graph) despite variations in the balance of supply and demand. Data from IMF (IMF Commodity Prices) www.imf.org/external/np/res/commod/index.aspx.

5.1. Behavioural Risks: Loss Aversion, Sticky Inflation and Capitalinertia

Oil price movements have downstream effects on production logistics and on transport and internal combustion engine operating costs in general. Oil prices have not significantly affected food prices in advanced economies [29]. This is not due to oil cost shifts not being significant but is due to the overall high costs of food retailing in advanced economies. In emerging economies, where food is

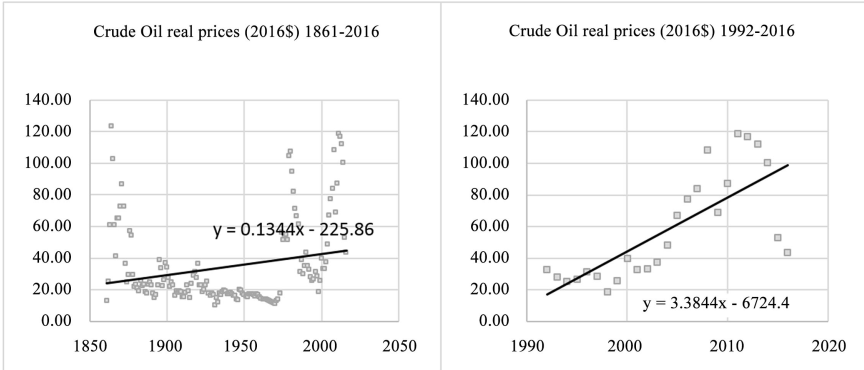

Figure 12. Oil prices: the present global economy's thermometer. Despite supply being cartel mediated (OPEC) there is a long term upward trend in the cost of oil (left hand side graph) and that trend has accelerated in the last 3 decades (right hand side graph) in the same period that the level of global mechanization has increased. Supply has not yet become limiting because rising prices have spurred increased exploration and technology development for extraction of previously uneconomic oil resources. Data from BP Statistical Review of World Energy 2017 (Underpinning data MS Excel file).

Table 1. Correlations between IMF Global Price Indices 1992-2017.

Linear regression correlation	Index Comparison
0.99	Energy Price Index to Commodity Price Index
0.91	Metals Price Index to Commodity Price Index
0.57	Industrial Price Index to Commodity Price Index
0.55	Agricultural Raw Materials Price Index to Commodity Price Index
0.99	Metals Price Index to Industrial Price Index
0.48	Energy Price Index to Food Price Index

Data from IMF (IMF Commodity Prices) https://www.imf.org/external/np/res/commod/index.aspx

cheaper, oil price increases do have a significant pass through to food prices [30]. In advanced economies, a food retailer's margins are eroded by rising energy costs. When energy costs drop, food retailers have typically exhibited reluctance to fully and immediately pass cost reductions onto customers. Food is not the only sector to demonstrate this behavior.

Cost increases in energy tend to disseminate broadly across a mechanized economy. Energy and other utility companies have demonstrated the same behavior. This phenomenon is common enough to be awarded its own economic terminology—sticky inflation. This is a behavioral response and is most likely attributable to loss a version by corporations when benefitting from increased margins following energy costs reductions.

The balance being assessed is one of future gain in custom and volume versus immediate increased margins from reduced operating costs and sustaining that as long as possible. Sticky inflation appears to be loss aversion behavior. Other sectors appear vulnerable to market inefficiencies arising from loss aversion. The amount of capital invested in fossil fuels and associated downstream industries which use oil product based internal combustion engines is one of the largest global markets for generic technology. Write off of those assets at any point will have an enormous financial impact and yet transition to other technologies for producers in particular is difficult to initiate due to loss aversion when the market for oil is pursuing a diminishing resource still in demand which increases its value per unit. Loss aversion at a strategic level, such as that described in this example, represents a significant capital inertia that policy makers need to take into account.

5.2. Externalities and Economic Inefficiency: Resource Entropy Explains Long Term Supply Cost Trends

The market is in effect, an entropy filter, preferentially consuming low entropy resources [31]. The consequences of this are apparent in the oil market (**Figure 13** and **Figure 14** and **Table 2**). As the lowest cost forms of oil have been increasingly drawn down and long term demand has been maintained, the net return on energy invested has decreased and the cost of resource provision has increased (see **Table 2**). A mechanized economy depends on capital, labor, energy and materials. The dependence of technology in general on exergy and hence energy resources creates interdependencies through the global economy that further complicates determination of cause and effect. The downstream effects of critical energy resources are now recognized; especially for oil [31] [32] [33] [34].

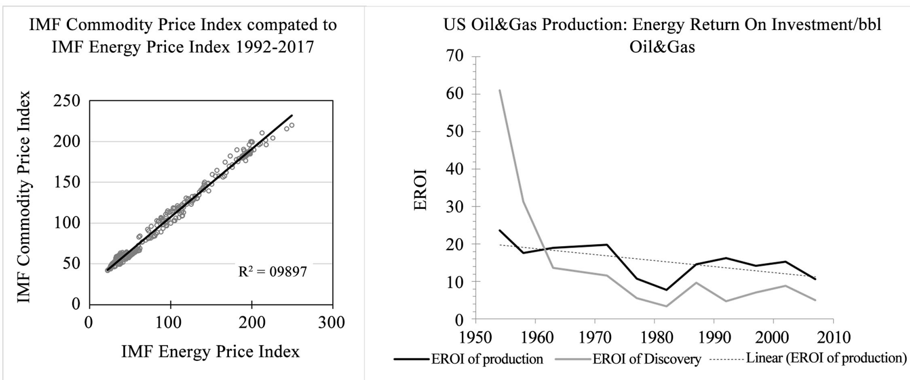

Figure 13. The mechanization of the global economy resulted in a very tight correlation between the real cost of energy resources and the real cost of material resources including commodities (left hand graph) for the 1992-2017 period. The market uses price/cost as its principal information and so exploits the lowest cost resources first, typically towards their extinction before substituting one resource for another. The fossil fuel industry is seeing its resource costs increase as lower cost conventional oil supplies become rarer (right hand graph: [33]. The entropy of a resource is a measure of its quality. Low entropy resources require less work to bring to market and so are lower cost. For oil and gas, low entropy resources are now dwindling because they were low cost and the market utilized them preferentially first (see **Table 2**). Data from reference [33] and IMF (IMF Commodity Prices) https://www.imf.org/external/np/res/commod/index.aspx

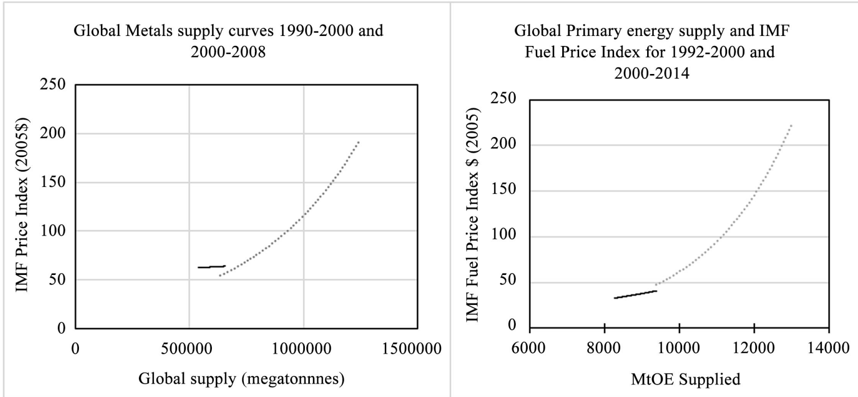

Figure 14. The mechanization of the global economy and the significance of the technology factor in growth make energy resources and metals two of the critical raw materials for provision of mechanized production capital assets. Over the last two decades, mechanization has accelerated within the global economy and surveys of supply of these materials have shown a super-exponential rate of supply—which matches a period of overlapping exponential growth in the global population and exponential growth in global *per capita* production as GDP. This evidence is supported by the global aggregate supply curves for metals and energy which both show an upward shift in the supply curves for the latter half of the 1990-2014 period (LHS 2000 to 2008 grey dotted curve; RHS 2000-2014 grey dotted curve)—the period coinciding with the highest rate of mechanization, which is the source of demand. The supply trend-lines also extend fully to the classic short-run-long-run form for 2000-2014 (grey dotted lines) implying that in this period demand is outpacing supply capacity. This characteristic is also consistent with increased demand driving the supply trend in these periods. The dark solid lines represents periods of a lower global aggregate level of mechanization (LHS 1990 to 2000; RHS 1992-2000); Oil elasticity date from reference [43]. Data from IMF (IMF Commodity Prices https://www.imf.org/external/np/res/commod/index.aspx and Barry, J.J., Matos, G.R., and Menzies, W.D., 2013, U.S. mineral dependence—Statistical compilation of U.S. and world mineral production, consumption, and trade, 1990-2010: U.S. Geological Survey Open-File Report 2013-1184, 6 p., https://pubs.usgs.gov/of/2013/1184/.

Table 2. Global oil supply composition 2016.

Production (million barrels/day)	Oil Type	Breakeven Price (US$/barrel)
20.6	Onshore Middle East	29
18.6	Offshore Shelf	43
2.77	Extra Heavy Oil	49
7.6	Deepwater oil	53
9.7	Onshore Oil-Russia	54
21	Onshore-rest of world	55
4.13	Ultra Deepwater oil	57
12.4	North American Shale Oil	62
2.75	Oil Sands	74

Data from reference [35] (IMF Working Paper WP/17/15).

The basic premise for resource entropy is very simple. The market acts on price, which means it tends to consume the lowest cost resources available until that resource is almost extinct; only then substituting for a higher cost similar resource, which by definition, should be the next lowest cost resource available. In physical terms the lowest cost resources are those requiring least work to bring to market; these are by definition the lowest entropy resources. This long term gradual depletion trend does not just apply to fuel (energy) resources; it also applies to material resources such as agricultural land (soil erosion) and minerals, including metal ores a critical component of the mechanized global economy).

Recent surveys of the state and quality of mineral resources confirm these trends ([36]-[41]. Mineral resources include a critical strategic resource for food production (Phosphorus) and also metals which are critical for the majority of current production technologies. Many metal ores now used as raw materials are of lower concentration and also require more physical work and more resources to bring to market; that in turn increases the amount of waste produced in bringing the resource to market which further increases the physical work requirement associated with the resource. Increasing entropy in the environment changes habitats and degrades natural capital. Costs of the entropy of production are not confined to the raw energy and material resources. Production has to discharge material to function. The discharge of wastes also creates costs which are borne somewhere in the economy even if the discharged materials are not completely (fulllife cycle) managed by producers. Where production fails to meet these costs, they are typically socialised *i.e.* passed on to the general population as public service costs.

Energy resources in particular are associated with a significant on-costs, which have been difficult to define because these costs have been falsely externalized. A physical assessment of technology and production costs shows that what are now defined as externalities are cost of production from physical factors of production. Mixed in with those costs are other cost burdens. For energy, these include subsidies. Currently both renewables and fossil fuels are subsidized, but the global level of fossil fuel subsidies ($490 Billion in 2014) was recently approximately four times larger than the global level of renewable energy subsidies ($112 Billion in 2014) [42]. The significance of resource entropy is that it is responsible for a persistently rising cost pressure on production that translates into an erosion of discretionary spending capacity for low and middle income groups, now including advanced economies, due to the reduced share of income to labour. While higher income taxpayers may pay higher tax per capita, the proportion of income as disposable income is across the majority of the population has a greater effect on spending potential. The disposable income of the majority is under greater pressure and less resilient than that of higher income groups under present macroeconomic policies.

5.3. Capital-Labour Share and Increasing Inequality

A risk associated with the finance industry and its overall impact on a national economy and on the global economy is now also being reported by several economists, including Hudson [44]. The risks identified are that that if the finance sector grows above a certain size in terms of share of GDP in an economy, it has destructive effects on the real (physically productive) economy including facilitating excessive (meaning ultimately unsustainable) debt. It may also divert capital required for development (especially at a time of attempted global growth) away from technology development for productivity and the necessary supporting infrastructure investments in the real economy [45]-[52].

Recent research has also shown that an excessively large finance sector in an economy will compete for highly skilled labour-labour which is also in high demand in key sectors of the real economy and has a high educational investment requirement. There appears to be an optimum size for a finance sector within a given economy with regard to the support and benefits it can offer the real economy, beyond which the finance sector will compete with the real economy and its production capacity for investment capital and highly skilled labour. There is also an optimum level of finance activity within an economy beyond which it erodes aggregate productivity in the overall economy [50]. This appears to result from investment in technology and the infrastructural support for technology being diverted from production in the real economy into the finance sector. Recently Picketty [8] [9] highlighted the level to which increasing wealth inequality had become embedded in the global economy. This factor is important in risk assessment for assessing the political sustainability of macroeconomic policy because severe inequality is related to social and political instability [53].

5.4. Capital-Labour Share and Increasing Inequality

In 2013, Picketty [9] reported on increasing wealth inequality and identified its cause as a shift in the previously constant share of capital and labour in total income. Picketty's initial proposed mechanism for this shift in the capital and labour share was a growth model; the rate of return on capital is greater than the rate of economic growth in the long term (an inequality, $r > g$). There is now a broad consensus that empirical data shows that income inequality is increasing, including advanced economies, but less agreement over how the distribution of wealth is changing. Factors to consider for wealth included inherited assets: a large part of global wealth is in land and property [23] [54] [55]. The assumptions for Piketty's growth model have been questioned e.g. Raval [56]. Ravel describes how Picketty's model has to assume an elasticity for labour and capital of unity and assume that the technology factor for productivity has been constant. There is some evidence for the former but more for a lower value for that elasticity and there is no definitive evidence or explanation for the technology factor for productivity remaining constant. The review of technology undertaken in this paper suggests that, in the form of mechanization, technology can both increase the exergy reach (the physical work capacity) of labour per unit of time (a labour displacement factor) as well as increase the opportunities for productive work (a labour demand factor). Given the development characteristics of technology that affect physical infrastructure and support physical production, much of that labour will be highly skilled or need retraining to a higher skills level.

The first form of mechanization, that leveraging physical work capacity, will also facilitate off-shoring for further cost reductions. The second form of mechanization (IT based) lends itself to *routinization*, which displaces middle-skill labour aggressively in advanced economies (IMF, 2017). These technology attributes imply that it is unrealistic to assess labour in terms of a single elasticity value. When we assess information utilization efficiency in the economy we are addressing the knowledge basis for an economy. In simple terms, there are significant investment differences required for low-skilled, middle skilled and high-skilled work.

Combining technology with labour has different outcomes and support needs, depending on what the structure of the host economy is and depending on a specific producers view of what the producer wants.

The capital-labour share is now shifting because labour is being displaced at an increasing rate by machine technology in the global economy [24]. Off-shoring can play a role in this but the *predominant* forces affecting income share and disposable income for the majority in advanced economies are technology and resource entropy; the former is reducing share of income and the latter is decreasing he disposable fraction of that income. The effects of technology on labour/capital share have been recently independently reviewed by the OECD/ILO [57] and IMF [24] and the conclusions derived are the same. The empirical data presented in these studies fits the pattern of technology development described here. For example, the OECD/ILO Report on G20 economies [57] [58] gives labour productivity, capital and labour share and investment data for 2000 to 2012. The hiatus in investment that occurred in 2008 was also a period within which the shift between capital and labour went into reverse and then stabilized after years of declining in favour of capital. At the same time as investment (which would include investment in technology) dropped, labour productivity also dropped. When labour productivity resumed in 2009, investment had begun to rise in advanced G20 economies.

When the physical factors relating to technology, labour, and capital and resource entropy are taken into account, there is no *long term* equilibrium in the market. There *is* a short term equilibrium but the physically inflationary effects of resource entropy have shifted that equilibrium in the last three decades and continue to do so. In comparison to the pressures on income for the majority, there is an emerging global "nouveau riche". The new wealthy are typically associated with globalized information technology services and financial services. These are typically large global financial and IT corporations which are multinational, whose advantages in a globalized world include the ability to easily move capital assets and choose between tax jurisdictions to their own advantage. Incumbent multinationals such as energy and minerals companies, are in comparison restricted by the physical restrictions of their raw materials and capital asset base and their potential future liabilities from destruction of natural capital. What most multinationals have in common is use of technology and global trade to maximize their economies of scale for operations, to a level that that smaller organizations cannot readily compete with.

6. Discussion

At this time, neo-classical macroeconomic policy unadjusted for physical and behavioural risk is fostering increasing income inequality and natural capital destruction on a global basis. That is a problem because such persistent increasing income inequality leads to social inequality which in turn increases political instability. That political instability risk is highest for democracies. The market failures and inefficiencies that are currently being allowed by governments run a risk of undermining the credibility of capitalism being compatible with values such as equality and justice. It is the view of the author that capitalism is an essential part of the solution to present macroeconomic and environmental problems, but its ability to deliver wider benefits across national and global economies is currently being undermined by government failures to set the ethical objectives and economic sustainability goals the global market *needs* to remain healthy and politically sustainable in the long term.

The issues identified by a physical analysis of the global economy, which also exist in national economies are:

1) Work capacity is fundamentally a function of energy supply and efficiency of information use
2) Neo-classical economic growth models have no physical science basis and thus fail to register the physical feedback effects of economic activity full production costs. The technology factor in neo-classical economic growth models has a physical basis: the energy required to do productive (exergy) and information utilization. Both have had profound effects on technology development and its economic consequences
3) Successful economy wide technology development requires provision of hard and soft infrastructure to maximize its benefits: the role for the provision and maintenance of that capacity and capability is for government and not individual producers
4) Technology (mechanization) is increasing the share of income for capital relative to labour
5) Incessant automation (mechanization) does not necessarily give the best outcome within a national economy and is disruptive; it is governments role with its overview of the economy (not that of individual producers) to manage that overall disruption
6) Behavioural economics has established the subjectivity of human decision-making in economics; this can result in significant economic inefficiencies such as sticky inflation. Again, it is the role of government to properly manage these effects downstream after they manifest themselves in the

economy that government is responsible for

7) Use of externalities in neo-classical economics masks the true cost of economic activity and allow production costs to be socialized—which has agreater impact on the spending power of the majority than of high income groups. They have also allowed governments to rig the global market significantly in favour of fossil fuels via fossil fuel subsidies
8) Resource entropy is increasing the full cost of production despite technological advances in production efficiency; these costs are typically socialized
9) The share of income versus that for capital for skilled labour in advanced economies (e.g. OECD economies) is now being driven in favour of capital by technology and in particular, by how IT can leverage physical work

The universe has several basic physical asymmetries. The market has at least one fundamental asymmetry—it acts on price information and thus flows in the direction of low price and low cost for basic resources. There is a physical mechanism that is driving this asymmetry—it is the second law of thermodynamics. The economic consequences of entropy will be persistently rising costs as the energy required to recover materials from the environment continues to rise, if governments fail to restructure national economies for long term economic sustainability (**Figure 15**).

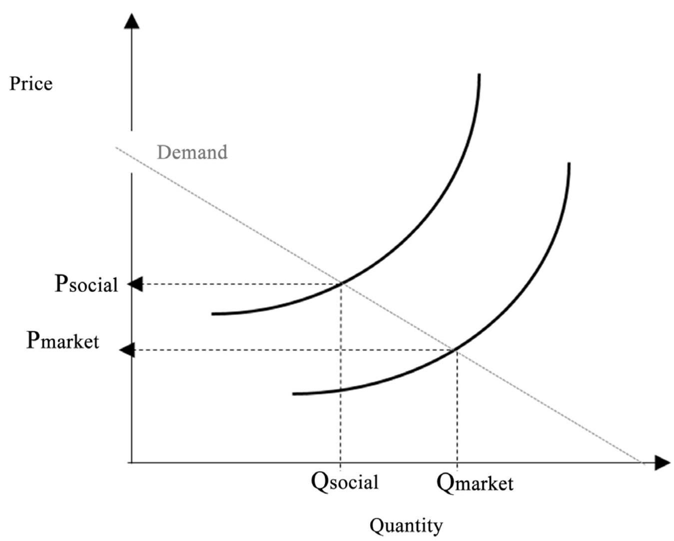

Figure 15. The long term effect of the doctrine of ‘externalities. Externalizing the true (full) costs of production results in significant socialization of costs for whole life cycle production and encourages overproduction and excessive downstream economic harm in relation to natural capital erosion, due to true production costs being underestimated. At the same time, on a long term basis, resource entropy is increasing the cost of living and thus eroding the discretionary spending and consumption capacity of low and middle income groups. The displacement of labour by technology (in different patterns for advanced versus emerging economies) is now exacerbating upward resource entropy pressure on costs by eroding the labour share of income. The result in advanced economies, where middle level skills now being rapidly displaced by technology, is that the consumption capacity of the majority is either being eroded or shifted to credit fueled consumption, contributing to increasing national debt levels in the latter case.

The first global economic strategic measure is to meet most of the Earths increasing total energy needs from renewable energy sources (which are all ultimately driven from outside the Earths boundary by solar energy). This will stabilize the cost of energy in future, with that cost stability being underpinned by concomitant reduction in GHG emissions and stabilisation in the rate of degradation of natural capital. The second global strategic measure is to minimize the cost of material resource entropy by moving global production in all sectors to a circular economy. Adopting circular economy approaches will increase the efficiency of material use and in the first instance, reduce the exergy and hence energy burden of utilizing progressively lower quality material resources.

Within national economies, governments should strategically plan for the first and second strategic investment and capacity building measures. Governments could make a virtue of them as national projects. In addition, governments globally need to better understand how technology and the size and reach of new global multinationals. On a national basis, governments should review the balance of their economies and rebalance the share of financial services in the economy if that sector is eroding overall growth and accelerating income inequality between the majority and high income groups. Government should also provide strategic technology development planning on a national basis that recognizes the strengths and weaknesses of that economy within the global economy. That strategic technology planning needs to consider the educational capacity and other "soft infrastructure" needed to support long term planning and economic growth. Taxation could be more progressive if adjusted on the based on entropy generated *per capita*, which would be the most representative measure of personal consumption; tax allowances could be regionally applied to adjust for technology impacts on regional share of income.

In future governments will also need to plan for long term shifts in population and how that impacts balance of payments and national economic capacity.

The reach and intensity of human global economic activity has now reached a level at which economic growth is destabilizing, due to the failure of government to set market goals that guide markets to long term sustainable growth. The requirement for government now is not to micromanage an economy but to manage it strategically for the long term, in order to secure long term sustainable economic growth to the benefit of the majority.

7. Conclusions

A macroscopic physical model of the global economy, based on its thermodynamic physical aspects is presented in this paper. The model presented introduces those physical elements into the Solow macroeconomic growth model. The integration of physical economic factors into the Solow growth model builds on the pioneering work of Ayres in demonstrating the role of exergy and hence the criticality of energy in the global economy and provides a coherent, physical description of technology in terms of its ability to leverage the physical work capacity of labour and the resources required. For the first time it links physical consequences of improvements in information utilization efficiency; meaning "knowledge", to other physical risks. This model concept (PGEM) provides a holistic explanation of how technology acts in the global economy and what its downstream risks are as physical resources are now placed under unprecedented demand. The PGEM also directly links economic activity to its environmental consequences and allows a better assessment of the risks to global economic efficiency arising from inadequately managed mitigation of the erosion of natural capital caused by present economic activity—of which the most immediate is climate change. Existing technologies can meet the climate change challenge [59]; it is market inefficiencies including short term planning, current industry size and loss aversion that prevent the fossil fuel industry from adequately moving within the energy market to renewables. None of these barriers are based on objective risks. Movement towards a circular economy to minimize material entropy effects within the global economy already occurs in some industries such as the water sector, already offering significant cost savings [60].

Physical factors, such as technology and resource entropy, are increasing overall global energy demand despite energy efficiency improvements. The quality of economically important material resources is decreasing which increases the energy burden required for their exploitation and waste management. This increases *per capita* energy demand. The structural response to these supply side cost increases need to be a faster global shift to renewable energy resources, to decouple energy provision from the Earths material resource limitations resulting from fuel resource entropy. *The same structural adjustment will minimize the cost of climate change*. Moving production to a *circular economy basis* is the overall material resource efficiency change required to stabilize material costs in the long term.

These measures will reduce long term supply side cost increases currently contributing to erosion of disposable income in advanced and other economies. Demand side measures managing physical risks are also needed. Governments need to begin to manage technology deployment and consider the wellbeing associated with human labour for some tasks where machines can substitute for labor, but in overall life cycle economic cost, there is in fact an advantage to maintaining a minimum level of human to maximize overall (life cycle) economic efficiency.

Governments need to begin to manage the negative downstream effects of technology which is currently driving income share down for labour relative to capital in advance economies. There is also a maximum optimal level of financial capacity in any national economy which governments need to manage better, along with long term planning for demographic trends. Under circumstances of physical limitations feeding back into costs of global resources, the market is currently invariably *inefficient* in the medium to long term.

Behavioural economics shows how part of this risk is based in human behavior. It is the role of government to manage that inefficiency and its associated inequality because these factors are ultimately political risks.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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